PHEV BATTERY COST ASSESSMENT

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TIAX's objective was to assess cost implications "at a high level" of selected battery chemistries and cell form factors being considered for PHEV applications.

Selected Battery Chemistries and Cell Form Factors

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Cost Assessments

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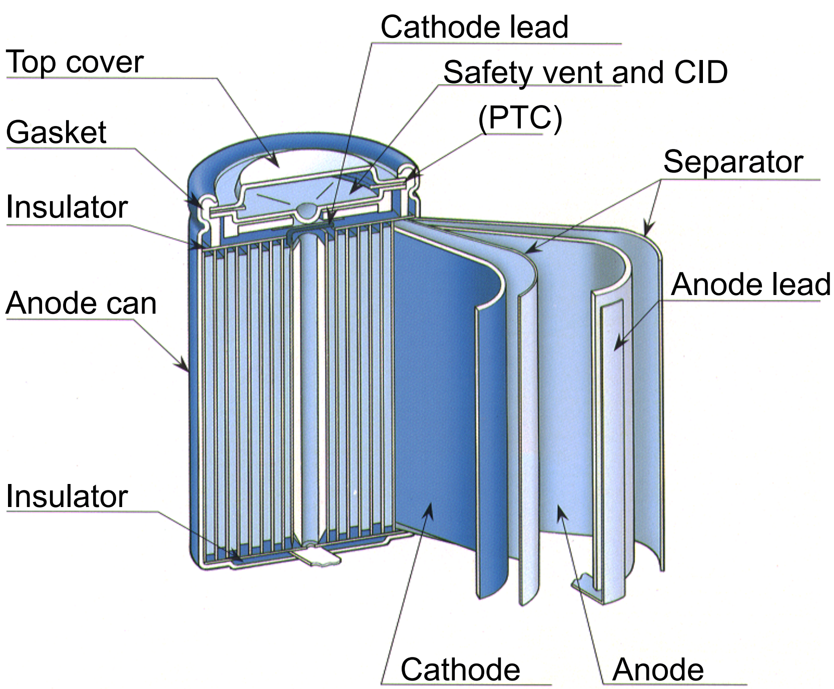
- ***Insight into the relative benefits of alternative chemistries***
- ***Insight into the cost implications of alternative cell designs***
- ***Identification of factors with significant impact on cell pack costs***
- ***Identification of areas where more research could lead to significant reductions in battery cost***

The program focused on four commercially available cathode materials and recently added one new cathode and anode material, and the impact of cell form factor on battery cost.

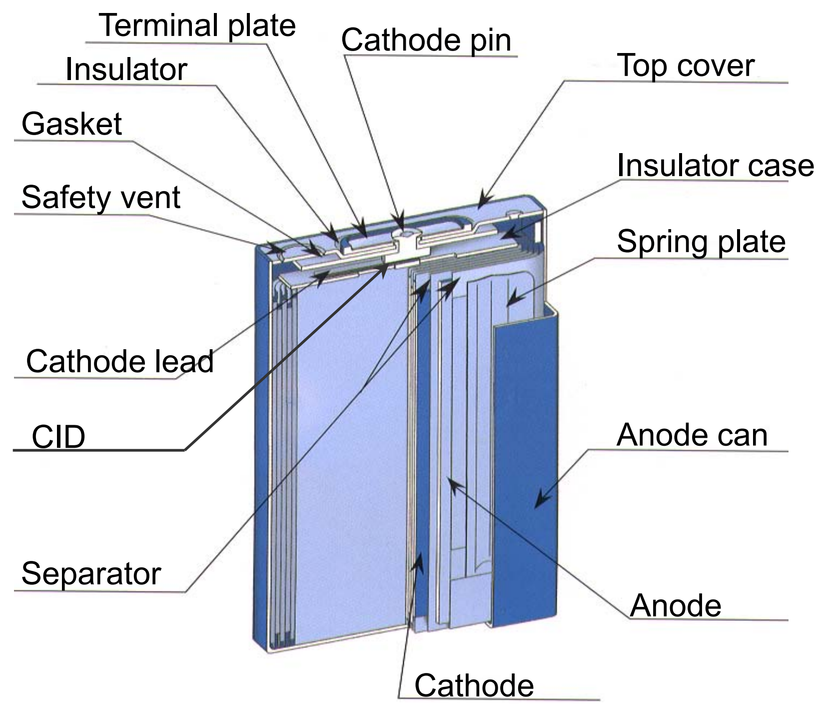
Materials	Description/Applications
NCA: Lithium Nickel-Colbalt-Aluminum Oxide	• Commercially available in high-capacity 18650 cells for computer notebooks (currently limited penetration) and in high-power cells for power tools. • Considered a “Generation 2” cathode material in DOE’s HEV program
NCM: Lithium Nickel-Colbalt-Manganese Oxide	• Commercially available in low-capacity 18650 cells for computer notebooks (currently limited penetration) and in high-power cells for power tools. • Considered a “Generation 3” cathode material in DOE’s HEV program
LMO: Lithium Manganese Spinel	• Commercially available in power tool batteries (currently limited penetration). • Under development for HEV and other vehicle technologies.
LFP: Lithium Iron Phosphate	• Commercially available in power tool batteries (currently limited penetration). • Under development for HEV, PHEV, and stationary technologies.
LL-NMC: Layered-layered Lithium Nickel Manganese Cobalt Oxide	• Under development for high energy and high power applications • Commercially unavailable
LTO Anode: Lithium Titanate	• In prototype stage for HEV/PHEV high power applications. • Produced in-house by battery manufacturers. • Commercially un-available on the materials market.

In addition to the cylindrical cell design, two alternative form factors were selected, including wound and stacked prismatic designs.

Schematic of Cylindrical Cell

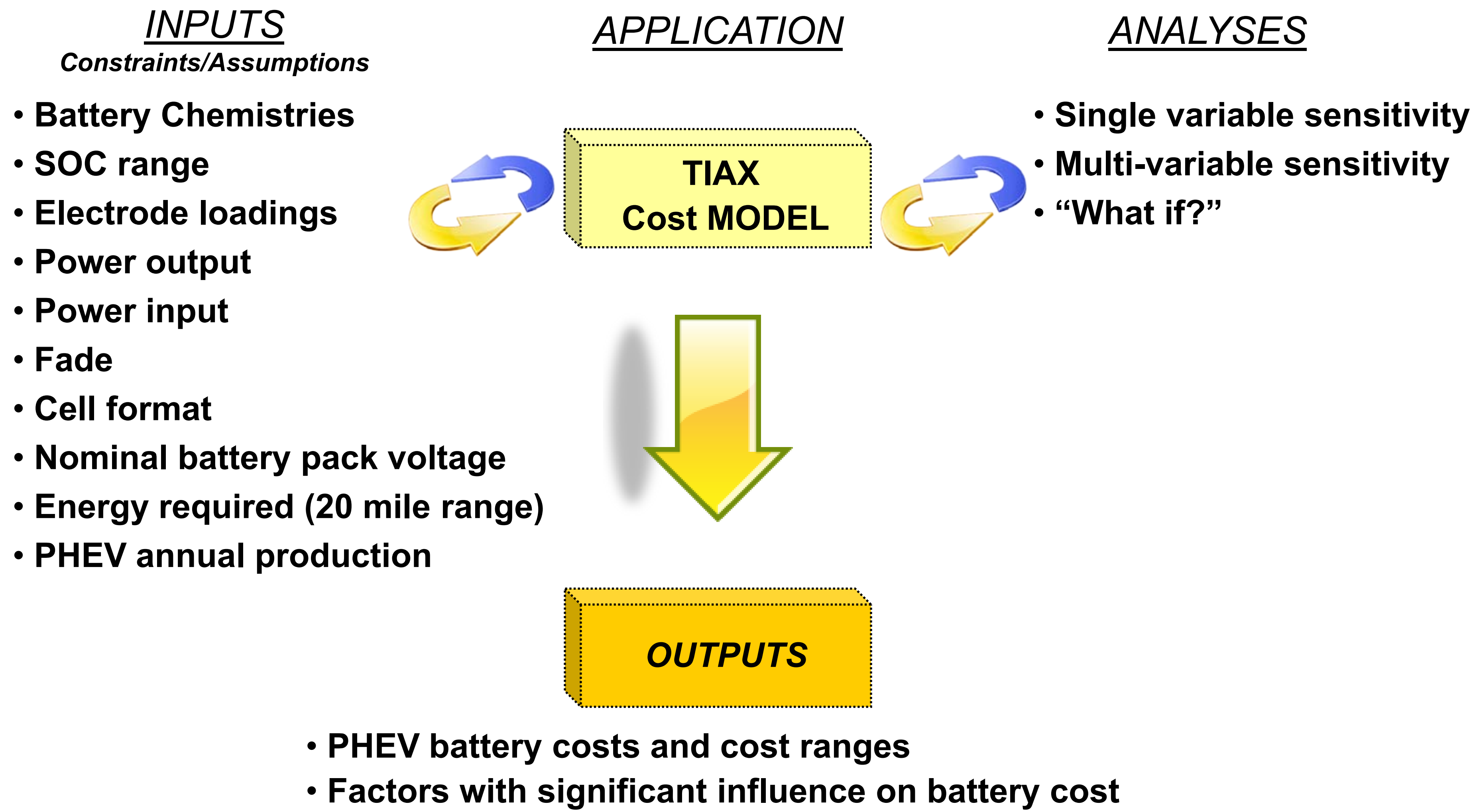


Schematic of Prismatic Cell



Wound or Stacked Electrodes

We employed a parametric approach in which TIAX's cost model was applied many times with different sets of input parameters.



Six different scenarios were considered for each cathode material meeting the 5.5kWh usable energy requirement in a 300V 20-mile PHEV battery pack.

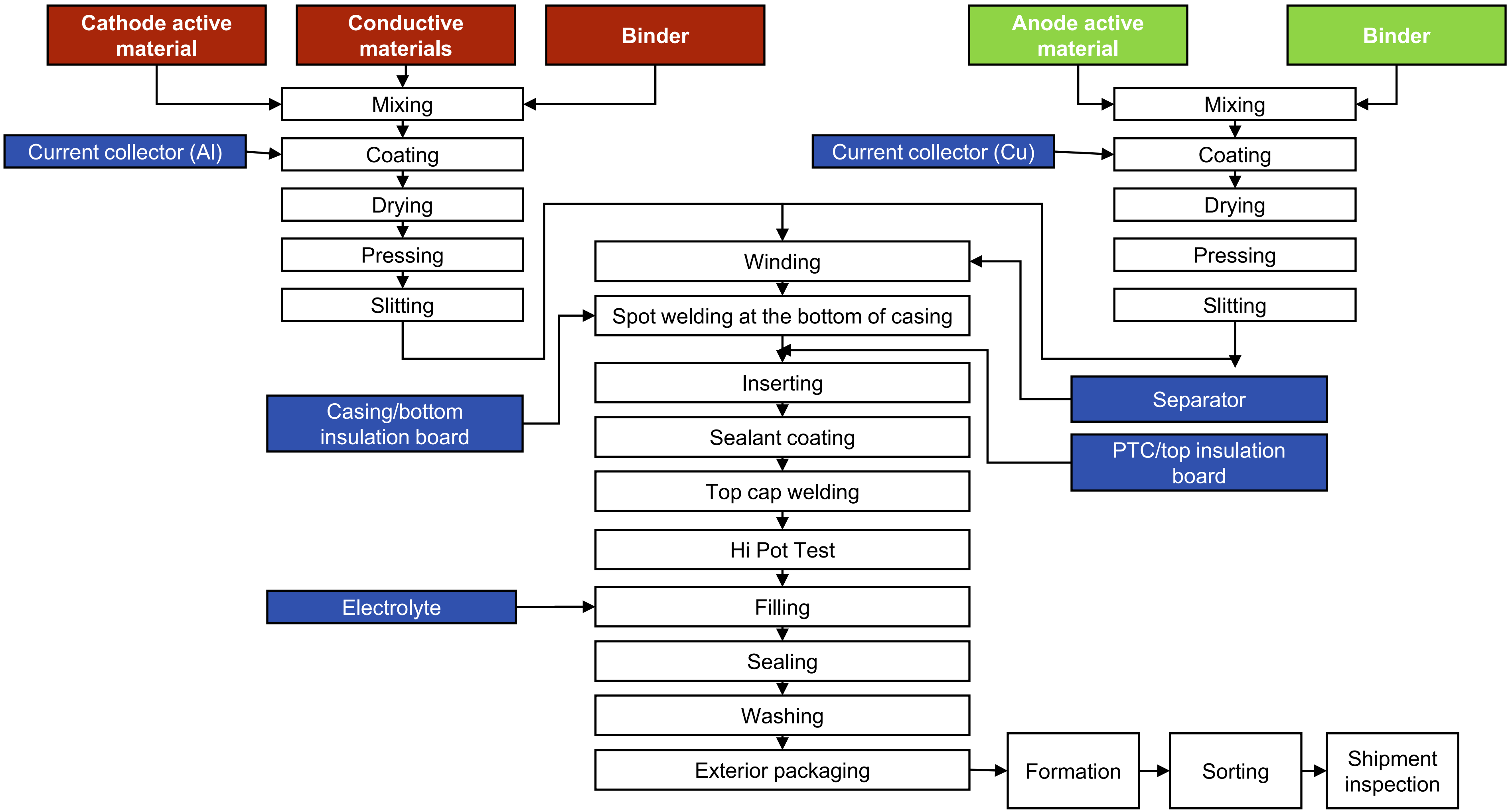
- Costs were modeled for a 300V PHEV battery pack that could provide 5.5 kWh of usable energy storage, satisfying AER and BM drive cycle requirements over the 20 mile urban drive cycle.
- Cells were designed for a range of electrode loadings (1.5-3mAh/cm^2) and fade characteristics (0 and 30%).

Design Scenario	Cathode Loading (mAh/cm^2)	SOC Range	Fade %	Total Energy (kWh)
A	1.50	80%	0	6.88
B	2.25	80%	0	6.88
C	3.00	80%	0	6.88
D	1.50	80%	30	9.82
E	2.25	80%	30	9.82
F	3.00	80%	30	9.82

Since Li-ion batteries of the design and size considered in this study have not been manufactured and tested, several key assumptions were made about the battery performance.

- **Battery Life:** The battery is assumed to be able to achieve the life defined in each of the selected scenarios.
  - **5.5 kWh usable:** Each design scenario to yield 5.5 kWh of usable energy (for 1C discharge) at end of life after accounting for assumed SOC limitation and fade.
  - **Nominal Li-ion cell energy:** energy for full discharge at 1C following charge to 4.2V.
  - **State-of-Charge (SOC) range:**
    - 10-90 % (i.e. battery size is 6.9 kWh nominal to deliver 5.5 kWh usable)
  - **Fade:**
    - 0% scenarios provide 5.5kWh usable at end of life w/0% fade (i.e. battery size is 6.9 kWh nominal to deliver 5.5 kWh usable @ end of life).
    - 30% scenarios provide 5.5kWh usable at end of life w/30% fade (i.e. battery size is 9.8 kWh nominal to deliver 5.5 kWh usable @ end of life).
- **Power Output:** The battery is assumed to be able to provide high power discharge pulses (40 kW for 2 sec., or 20 kW for 100 sec.) even at the lowest SOC.
- **Power Input:** The battery is assumed to be able to accept high power recharge pulses (30 kW for 10s) except when the battery is at a high SOC.

The TIAX cost model was based on typical process steps currently employed to produce Li-ion cells in large quantities, most typically 18650 cylindrical cells.



Reference: Kozawa and Yoshio, "*Lithium-ion Secondary Battery – Materials and Applications*", Nikkan Kogyo Shinbunsha (1997)

Key model cost inputs were identified and a likely range of values established for each one based on extensive discussions with materials producers.

Materials*	Low Value	Baseline	High Value
Cathode – NCA ($/kg)	34	40	54
Cathode – NCM ($/kg)	40	45	53
Cathode – LFP ($/kg)	15	20	25
Cathode – LMO ($/kg)	12	16	20
Cathode – LL-NMC ($/kg)	24	31	39
Anode - Graphite ($/kg)	17	20	23
Anode – LTO ($/kg)	9	10	12
Separator ($/m^2)	1.0	2.5	2.9
Electrolyte ($/kg)	18.5	21.5	24.5
Cell components ($/cell)	2.1	2.5	2.9

25% range used for most other material costs.

*To assure year-to-year consistency, values employed in Year 1 of this work have been fixed.

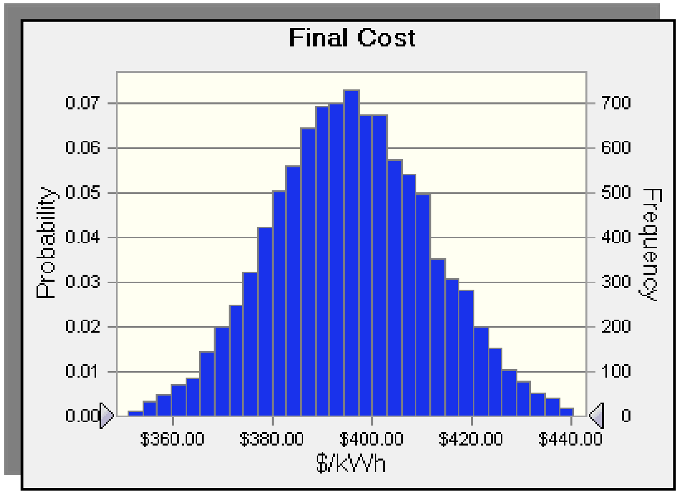
"Baseline" values were used for *single point* projections of cell costs. Low and high values were used in multi-variable sensitivity analyses to generate *cost probability* curves.

Key model process inputs were identified and a likely range of values established based on discussions with equipment and battery manufacturers.

Cost Factor	Low Value	Baseline	High Value
Anode/Cathode Coater Line Speed (m/min)*	4	5	6
Process Yield (%)	98	100	100
Wage Rate ($/hr)	21	25	29
Equipment cost	-25%	*	+25%
Throughput**	-25%	*	+25%

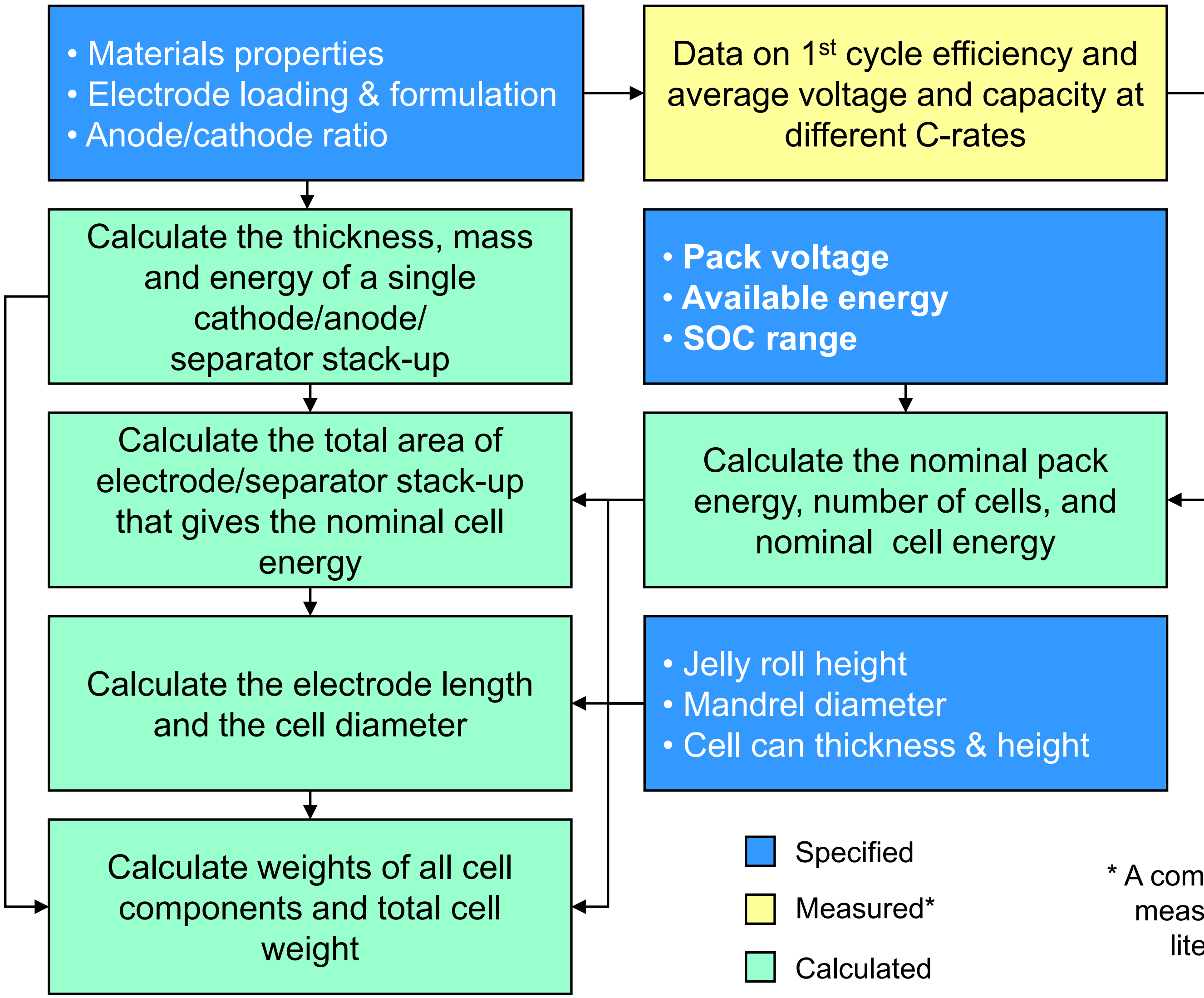
* Double side simultaneously; **All automated processes

These value ranges along with material cost ranges were used as inputs for single variable sensitivity analysis and multivariable estimates in distribution of the final pack cost using Crystal Ball® risk analysis software‡.



‡ **Crystal Ball®** *is a trademark of Decisioneering, Inc.,* www.decisioneering.com

Cell designs are built up from specific electrode properties.



* A combination of TIAX measurements and literature data

For example, a scenario, providing 5.5kWh available (9.82kWh total) energy at a moderate (1C) rate and 300V average pack voltage results in specific cell designs for each chemistry.

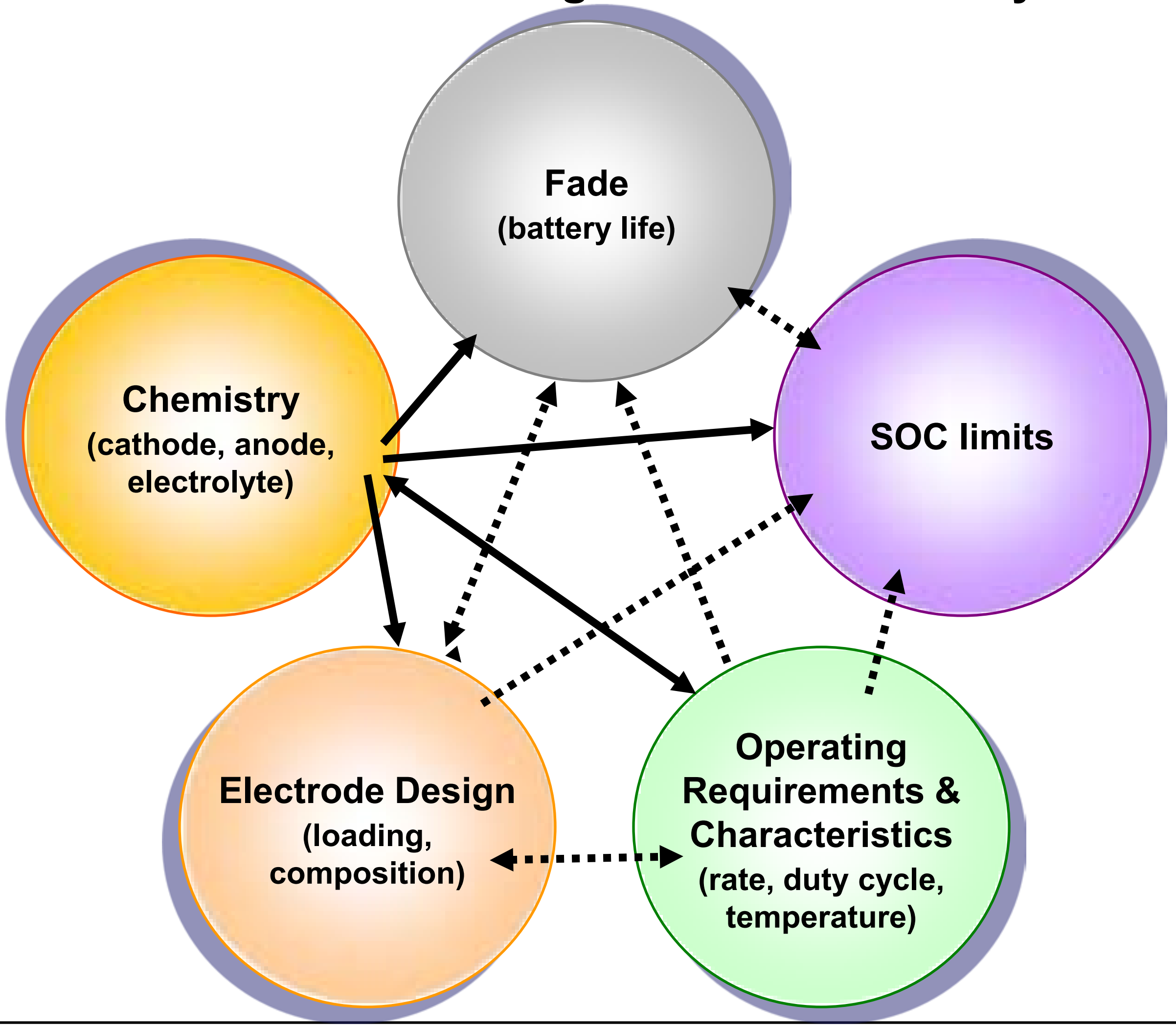
	NCA Graphite	NCM Graphite	LFP Graphite	LMO Graphite	LL-NMC Graphite	LMO LTO
Loading (C/5 mAh/cm^2)	**3.0**	**3.0**	**3.0**	**3.0**	**3.0**	**3.0**
Cell diameter (cm)	5.0	5.1	5.4	5.4	5.0	5.8
Cathode active mass (g)	201	220	233	316	163	313
Anode active mass (g)	129	127	113	107	151	209
Electrode length (cm)	430	436	413	407	450	403
Cell mass (g)	779	810	843	917	768	1091
# Cells per pack	82	81	91	77	92	121

- Initial LL-NMC packs would require anywhere between *10% to 40% less cathode* active material by weight, but at least *30% more graphite*, to account for high first charge capacity and low first cycle efficiency.
- LTO packs require approximately *60% more cells* to reach 300V specification and, in total, approximately *60% more cathode active material* to satisfy the energy requirement. They are also almost a *factor of two bigger and heavier* on cell only basis vs. graphite.

Care must be taken when directly comparing materials on mAh/cm² basis, since cell designs with equivalent capacity loadings implicitly favor high voltage materials and do not penalize low capacity materials.

- All of the material comparisons have been performed on the equivalent mAh/cm^2 active material loading, fade, and SOC range.
- This approach intrinsically **favors high voltage materials,** resulting in a smaller number of cells to achieve the same pack voltage, shorter electrodes.
- This approach also **does not penalize low capacity materials**, which lead to higher mass loadings and thicker electrodes, allowing for a lower ratio between the inactive and active cell components.
- ***Whether a particular cell design can meet the power and life requirements within the specified fade and SOC ranges must be determined experimentally.***
- In addition, optimal cell design will be different for each chemistry.

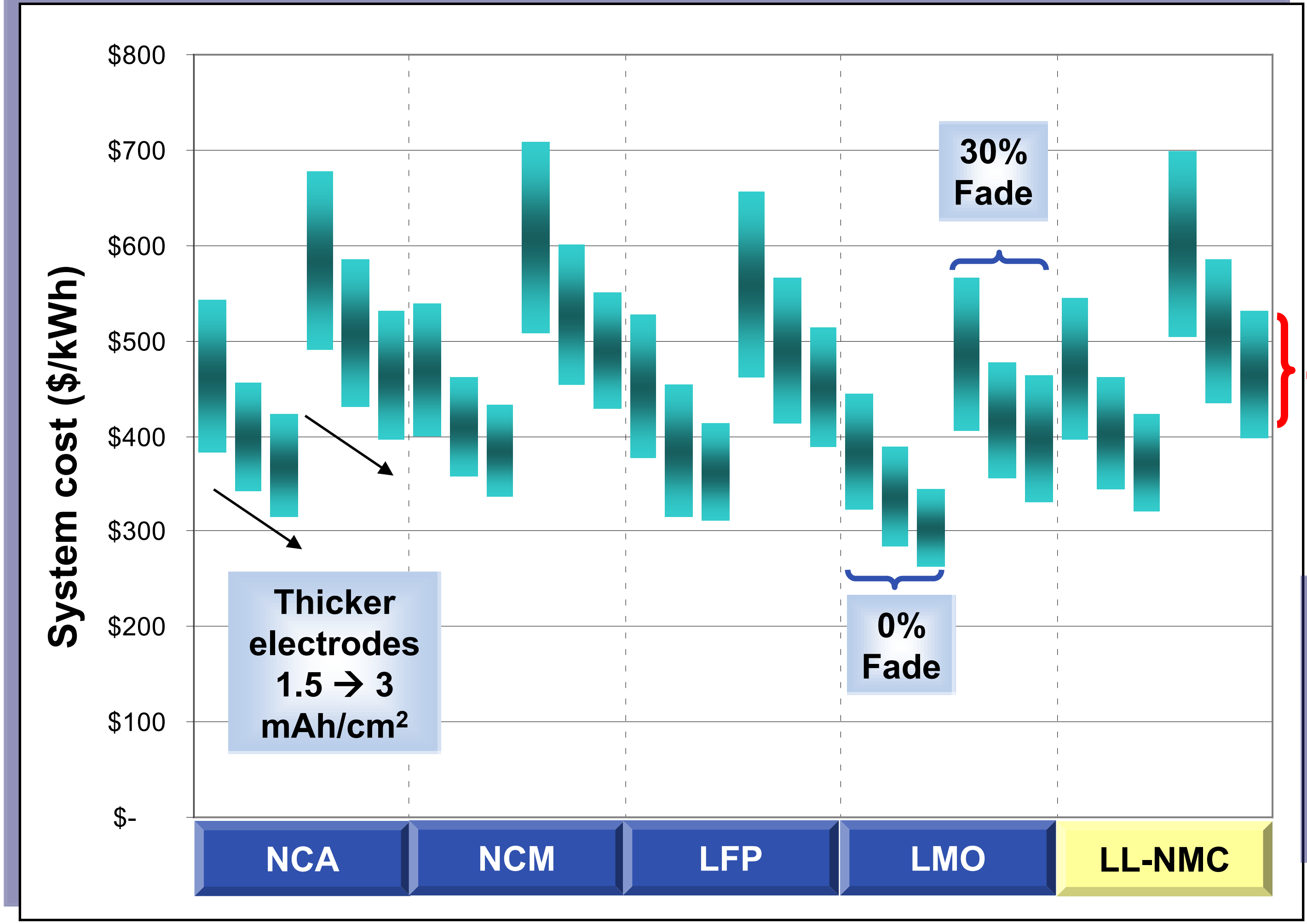
Optimized cell designs will inevitably be determined by complex *inter-relationships* between operational requirements/characteristics and design parameters, factors that cannot be integrated into this study at this time.



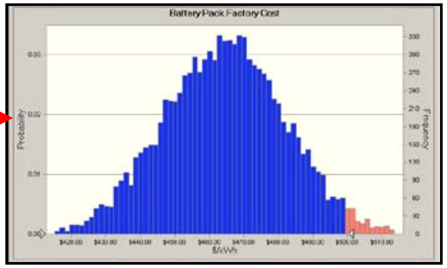
Alternate cathode and anode chemistries

Prismatic Form Factor Cell Designs

There is significant overlap in battery costs among the five cathode classes, with wider variation within each chemistry based on the electrode design than between chemistries.

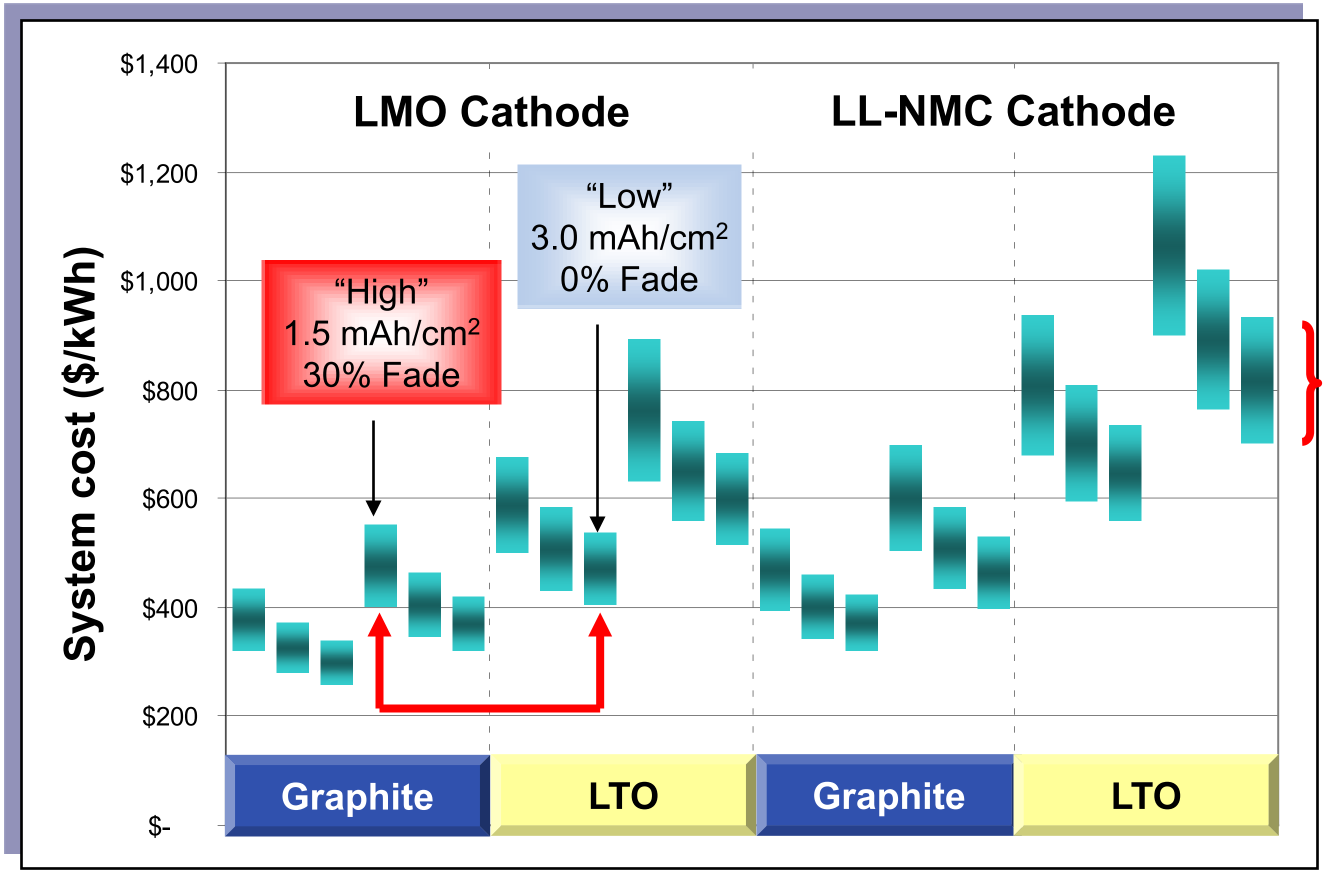


Cost Histogram

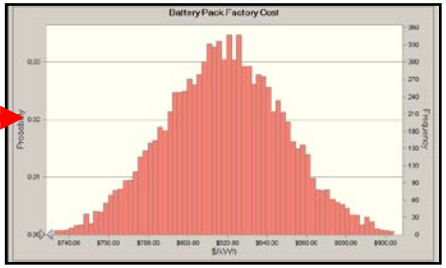


Cost range includes uncertainties in input parameters. Minimum and maximum obtained from multivariable Monte Carlo uncertainty analysis.

Cells employing LTO anode are significantly more expensive than graphite anode packs, with the "low" cost LTO cell designs comparable in price to "high" cost graphite designs.



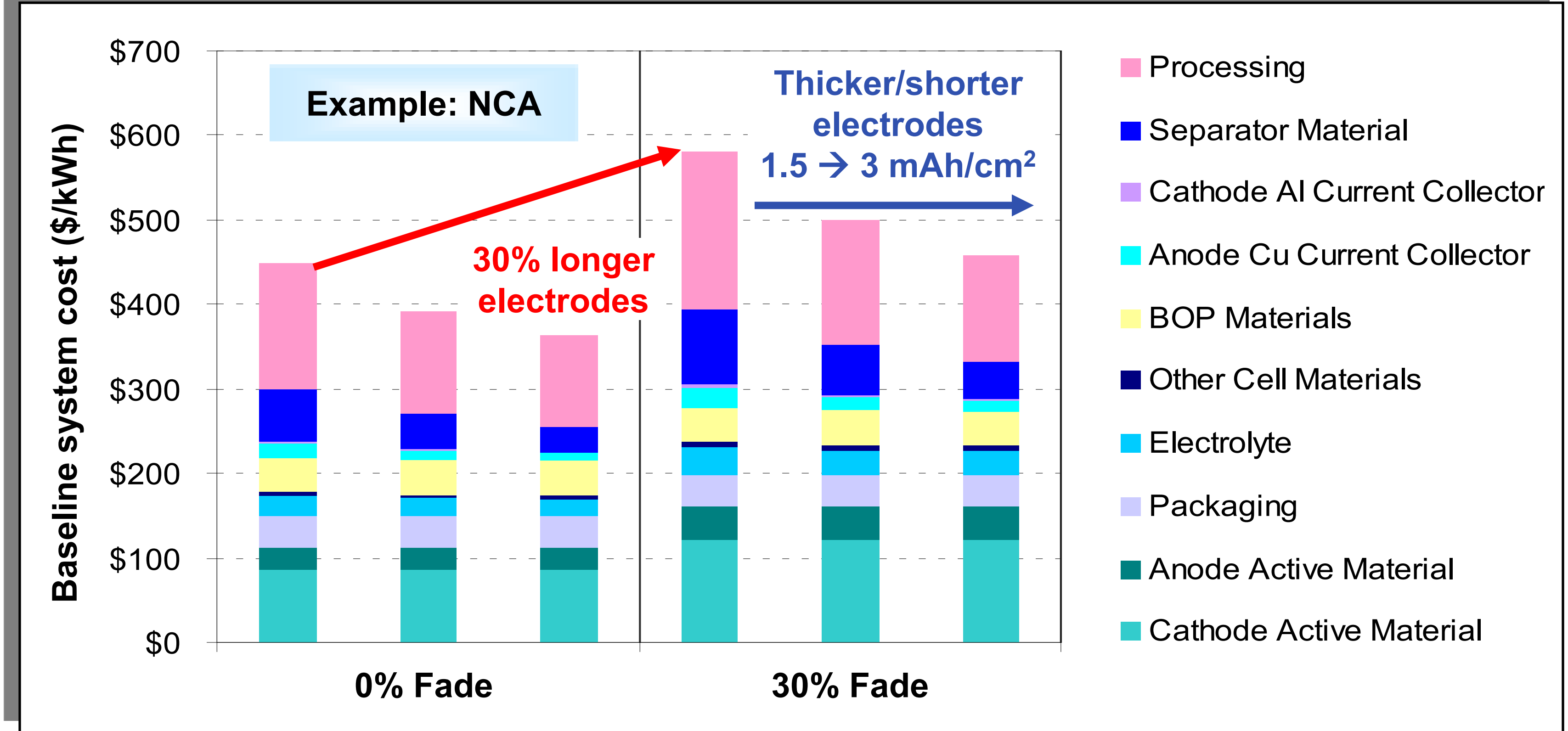
Cost Histogram



Cost range includes uncertainties in input parameters. Minimum and maximum obtained from multivariable Monte Carlo uncertainty analysis.

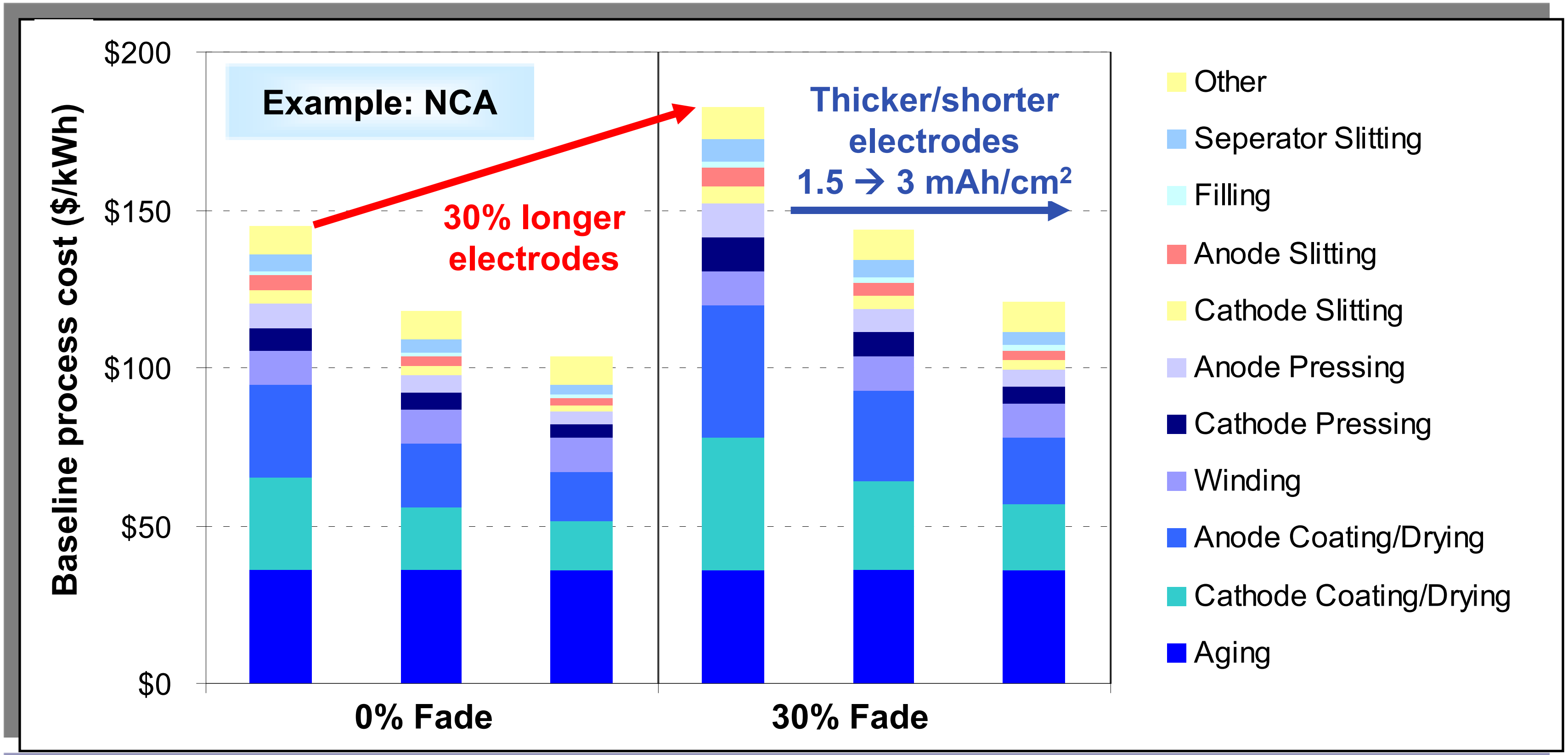
Note that to fully realize the benefit of LTO, secondary benefits outside the parameters of this cost study, must be considered (e.g. fast charging and an extended battery life).

Battery system cost is a strong function of electrode design – the ability to use thicker shorter electrodes leads to a lower contribution of inactive materials to the final system cost.



- Cathode active material cost contributes 19-27% of the final pack cost
- Utilization of thicker electrodes leads to significant reduction in separator and Cu current collector materials cost contribution and an overall reduction in the processing costs.

The ability to use thicker shorter electrodes also leads to significant reductions in electrode fabrication costs, especially in the coating and drying process.



- Cell aging, cathode and anode coating and drying, and electrode winding account for over 70% of the total process costs for all electrode designs
- Utilization of thicker electrodes leads to significant reduction in the cost of electrode coating/drying, slitting, and pressing.

*Process costs: equipment and plant depreciation, tooling amortization, equipment maintenance, utilities, indirect labor, cost of capital, fabrication and assembly labor

To help understand if and how battery cost might be further decreased, we developed four "what if" scenarios to test the impact of *extreme* values of related input parameters.

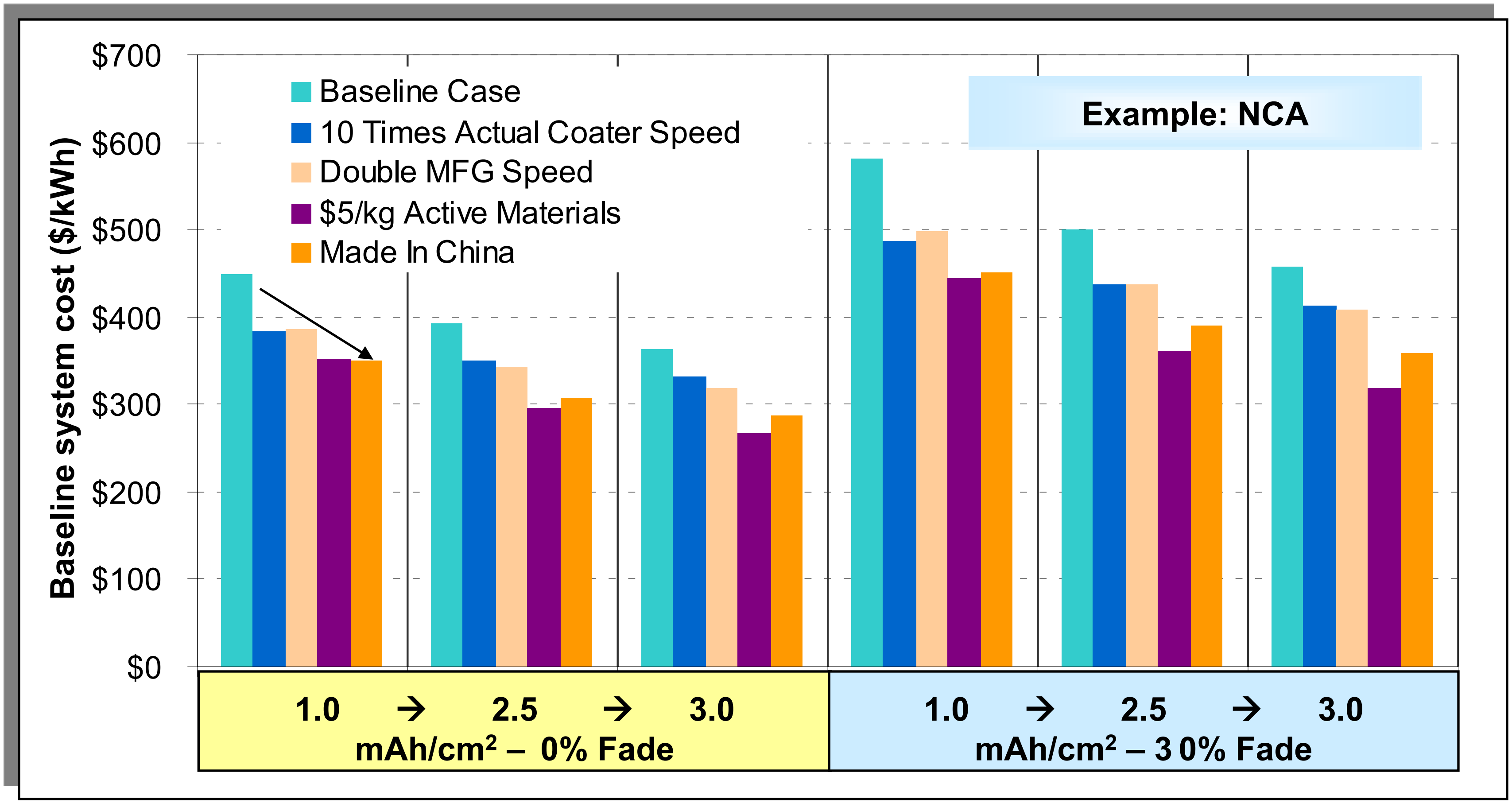
"WHAT IF" Scenarios (applied individually to Base Scenarios)

1. Increase coater speed by a factor of 10 from 5 m/min to 50 m/min
2. Double all manufacturing process speeds
3. All cathode and anode active materials cost $5/kg
4. "Made in China"

Assumption Variables	Baseline Cases	Made in China Cases
Labor Rate ($/hr)	25	0.67*
Equipment Discount Factor (%)	100%	67%**
NCA Cost ($/kg)	40	28
NCM Cost ($/kg)	45	38

* Bureau of Labor Statistics, Department of Labor, " International Comparisons of Hourly Compensation Costs in Manufacturing 2006"; published in 2008
** The Boston Consulting Group white paper, " Made in China: Why Industrial Goods Are Going Next"

A 15 – 25% cost reduction can be achieved for NCA systems by decreasing the cost of all active materials to $5/kg (a factor of 4-8) or taking advantage of cheaper labor, materials, and equipment as in the “made in China” case.



How realistic are the “What-if” scenarios?

Increase coater speed by a factor of 10 from 5 m/min to 50 m/min

- State-of-the-art coaters can run at 10-15m/min (double sided).
- State-of-the-art coaters are targeting a 2-fold increase in width to 120 cm, without loss of uniformity.
- This suggests that 3-5 fold increase in coater speed is reasonable.

Double all manufacturing process speeds

- Cathode and anode coating and drying, cell aging, and electrode winding account for over 70% of the total process costs for all electrode designs.
- Rate of winding for SOA equipment for high capacity cells is approaching that of 18650 cells at ~40cm/s and is unlikely to increase significantly.
- Aging time is unlikely to decrease significantly to maintain adequate quality control.

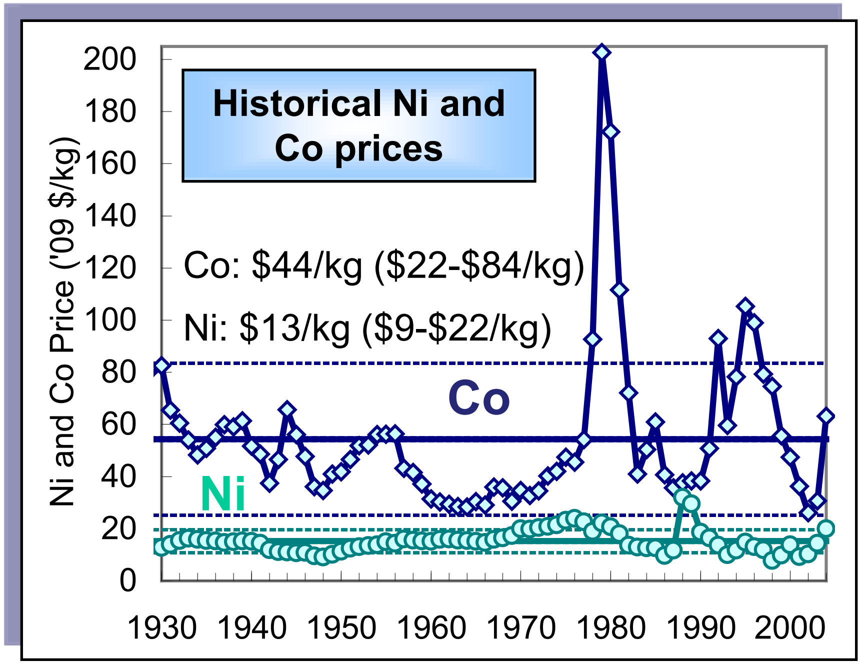
“Made in China”

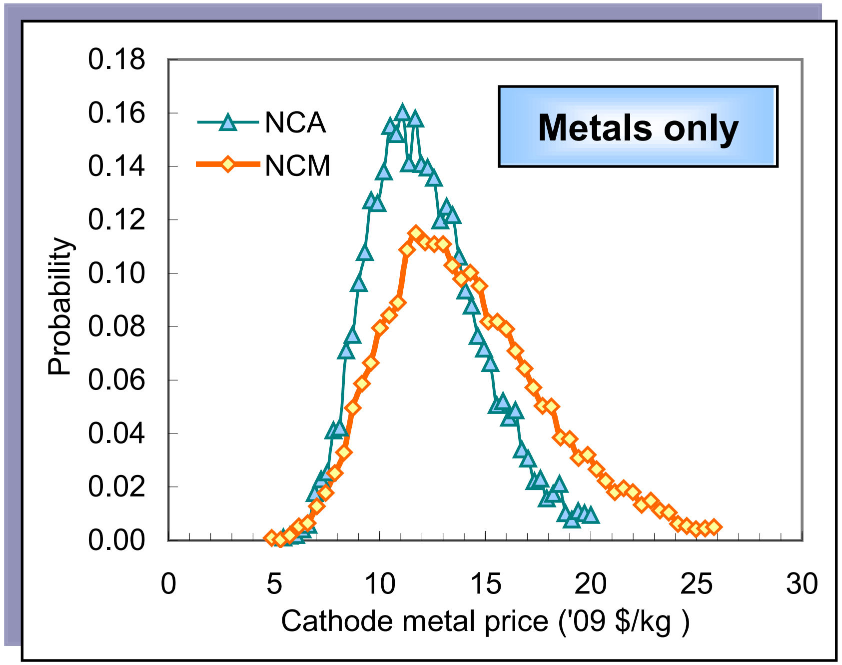
- Labor rates are unlikely to change, however, the number of operators per station can decrease with improved mechanization.
- With learning curve, equipment costs can decrease slightly.

How realistic are the “What-if” scenarios?

All cathode and anode active materials cost $5/kg

- Graphite is an established commercial product and is unlikely to see substantial cost reductions.
- The cost structure for cathodes typically reflects processing (~$3-6/kg), metals cost (market value), other raw materials (~$5-10/kg), and profit.
- For example, lithium metal oxide prices will reflect the price volatility of Co and Ni, leading to metals (only) cost contribution of $11(-3/+6)/kg for NCA and $13(-5/+8)/kg for NCM.





Source: USGS, *Historical Statistics for Mineral and Material Commodities in the United States*, 2006.
All data adjusted to 2009 Dollars using Bureau of Labor Statistics’ Producer Price Index for *Metals and Metal Products*.

Within the PHEV battery scenarios modeled and evaluated, cathode active material cost by itself is not a major factor in driving system cost changes.

- Higher fade and lower cathode capacity loading (i.e., longer electrode length) lead to higher battery cost.
- The results of an extreme “what if” analysis to test the impact of reducing the cost of active materials by as much as 90% reveals the impact on battery cost to be in the range of 15 – 25%.
- While initial LL-NMC has high capacity and a low content of the Ni and Co transition metals, its low first cycle efficiency and low average voltage lead to pack level costs that are comparable to NCA and NCM.
- High average voltage and low gravimetric capacity for LTO relative to graphite, lead to more expensive pack designs with higher number of cells and longer electrodes.

Cost of cathode active material is a somewhat less important factor in battery system cost than might have been thought.

PHEV battery configurations modeled in this study resulted in battery costs (COGS) ranging from $264/kWh to $710/kWh, or $1452 to $3905 for 5.5 kWh usable power.*

* These cost ranges were the output from the statistical, *multi-variable sensitivity analysis*.

- *Upfront cell design is a critical factor in battery cost.*
  - Electrode loading (i.e., electrode length) seems to be more significant than cathode active material cost, within the ranges evaluated.
  - *Active materials' influence on cell design has greater impact on battery cost* than does the (cathode) active materials' cost itself.
- *Manufacturing processing speed matters.*

Projected costs for PHEV batteries are largely in a similar range, excluding the NAS report which suggests significantly higher estimates.

Source	Estimate (per usable kWh)	Comments
TIAX	• $265-$710/kWh for 20mi PHEV	• Lower bound for high energy designs with low fade and low cost materials and equipment and high throughput rates. • Upper bound for high power designs with 30% fade and more expensive materials and equipment and low throughput rates.
Portable Market	• 18650 cell: $200-$250/kWh • Laptop pack: $400-700/kWh	• 18650 cells are a standardized Li-ion design currently produced in volumes approaching 1 billion cells/year worldwide (~ 10GWh/year equivalent to 1 million PHEVs/year), using the most highly automated processes currently available in the industry. Primarily based on $LiCoO_2$ cells.
ANL*	• $290-$330/kWh for 40mi PHEV • $490-$600/kWh for 10mi PHEV	• Cell designs with NCA, LFP, and LMO cathodes and graphite anodes. • Assumes 70% usable energy.
NAS**	•$1250-$2000/kWh by '2010 •$800-$1275/kWh by '2020 •$720-$1150/kWh by '2030	• Estimates for a PHEV-40 based on literature and discussions. • Assumes 50% SOC range, 20% fade, and 2 x markup from cell to pack costs.

**EVS International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, 2009

*Transitions to Alternative Transportation Technologies – Plug-in Hybrid Electric Vehicles, National Academies Press

These results point to a three-pronged approach in emphasizing specific areas of research with potential for reductions in battery cost…

Materials

- Materials that support high power, and a wide SOC range
- Materials that provide minimal fade, impedance growth and calendar aging
- Materials with higher specific capacity and higher average cell voltage

Cell/Electrode

- New chemistry, electrolytes, and electrode designs permitting shorter, thicker electrodes
- In general, chemistries and designs that enable lower overall electrode area per battery and minimize battery size will reduce cost.

Manufacturing

- Identification and adoption of advanced processing technologies to significantly increase *coater/dryer speed* and/or *other unit operations significantly* (enabled by materials or electrode engineering)
- Fundamentally different electrode preparation processes

...while meeting target requirements for power, energy, and life.

Ongoing Work

- Finalize Cost Projections for LTO
- Finalize Cost Projections for Layered-Layered NMC
- Finalize Cost Projections for Cylindrical versus Prismatic Form Factors
- Cost Reduction Strategies
- Cost for High Power, Low Energy – Energy Storage System (LEESS) for Power Assist Hybrid Electric Vehicle Applications